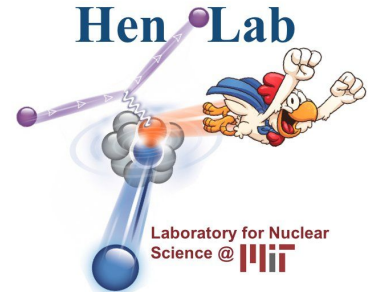


Towards The First Measurement Of Differential ν_μ -Argon Charged Current Single Transverse Variable Scattering Cross Sections

A. Papadopoulou for the  Collaboration
apapadop@mit.edu

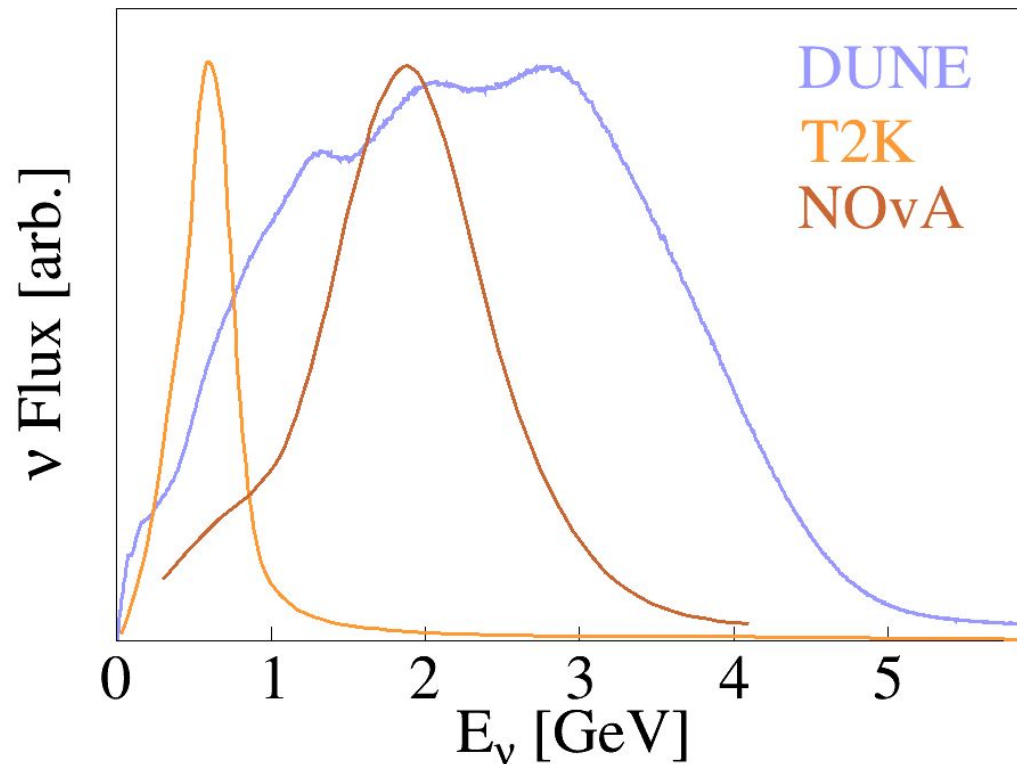


New Perspectives, June 16-20 2021



Why Precision Cross Sections Measurements?

Oscillation measurements rely on unprecedented understanding of ν -nucleus scattering



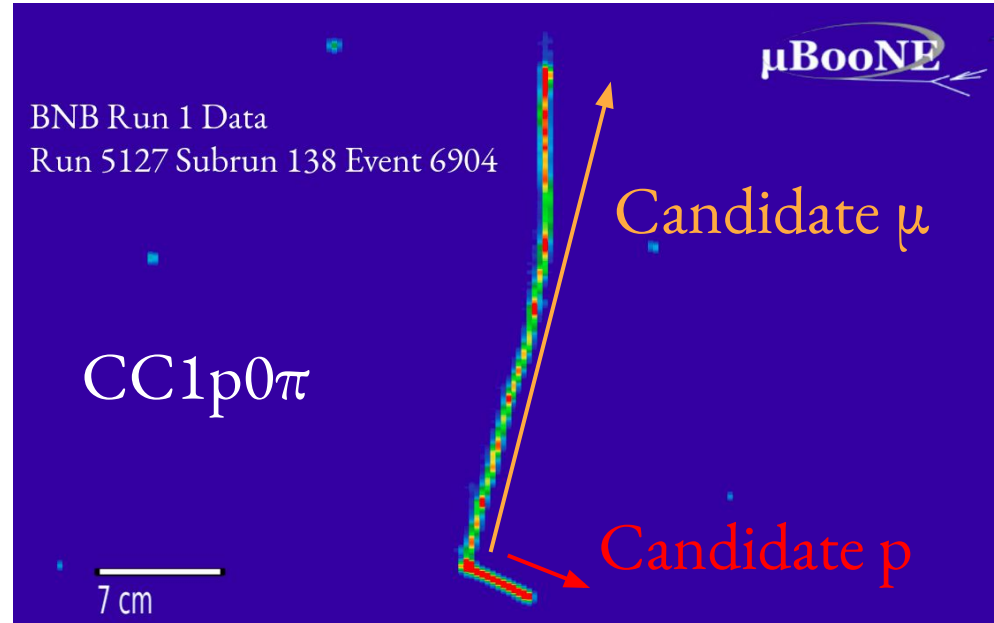
BUT ... many known unknowns

- Wide ν energy spectra
- Fermi motion
- Multi-nucleon effects
- Final state interactions (FSI)
-

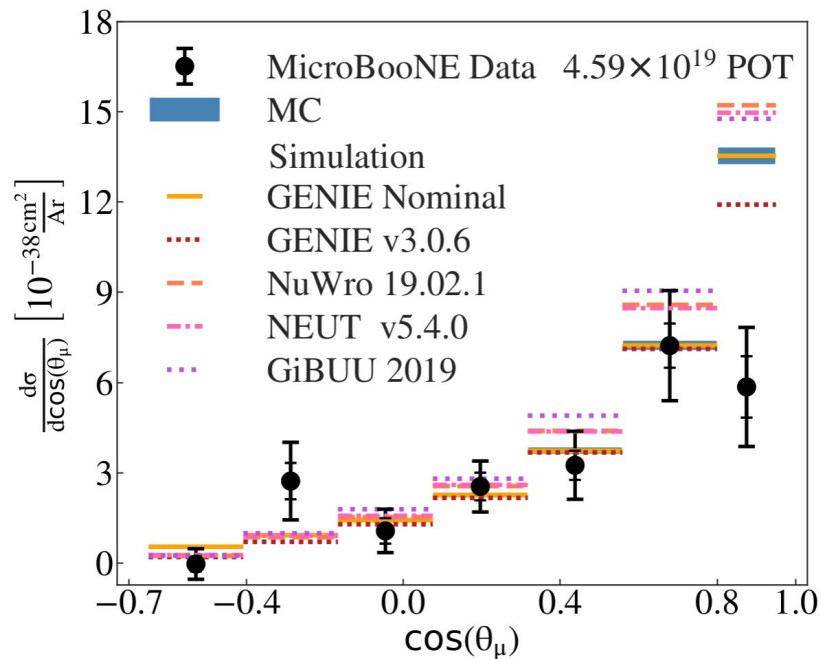
CC1p0 π Interaction Channel

Simple topology, dominant at energies relevant for MicroBooNE

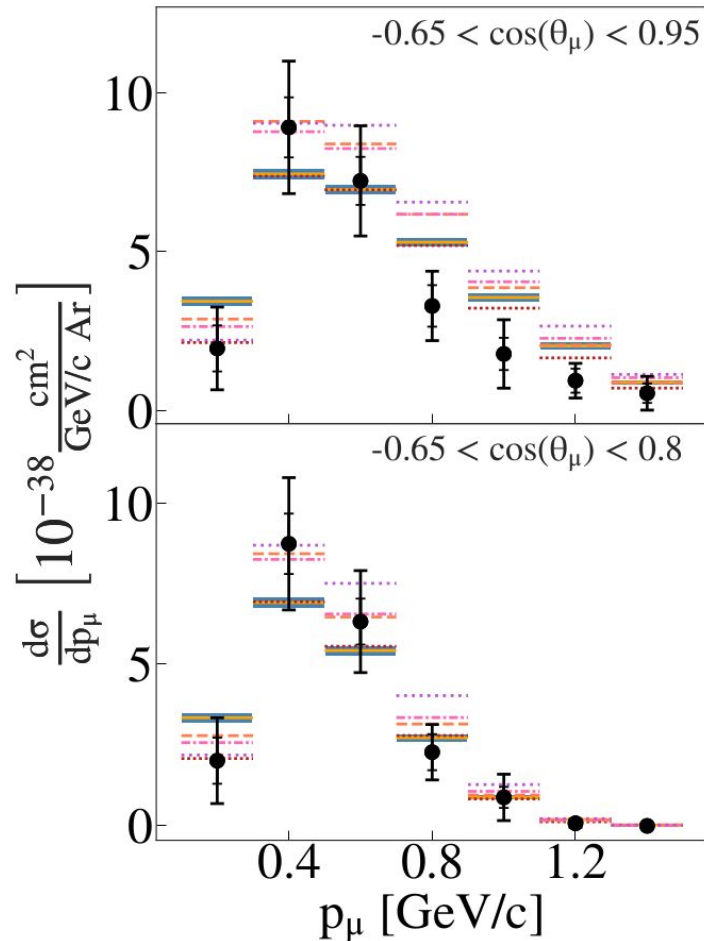
- Single muon $P_\mu > 100$ MeV/c
- Single proton $P_p > 300$ MeV/c
- No neutral pions
- No charged pions with $P_\pi > 70$ MeV/c



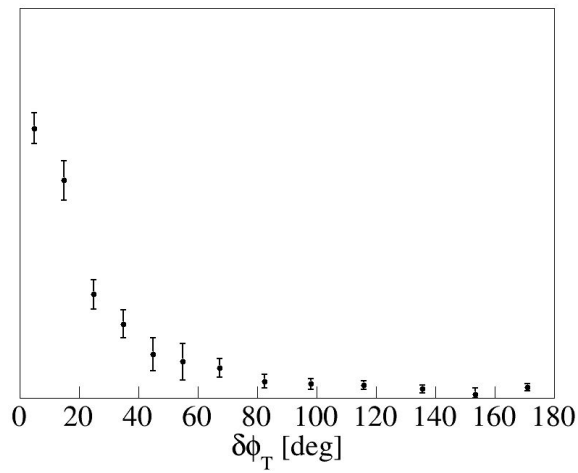
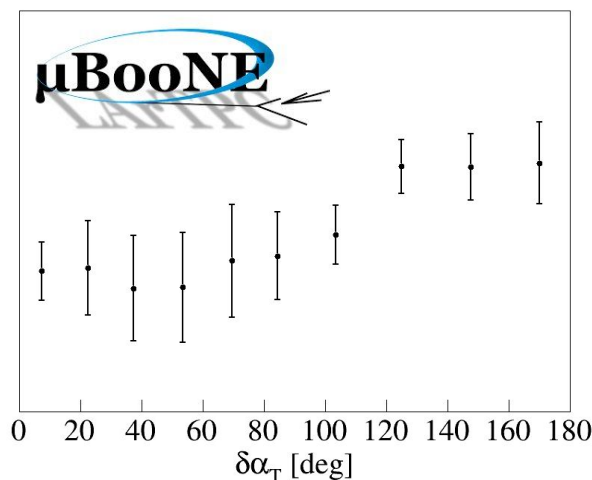
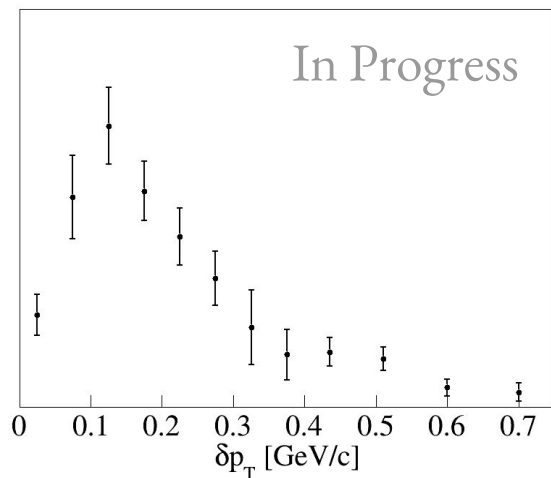
First Analysis Identified Regions Where Improvement Is Required



Phys. Rev. Lett. 125, 201803 (2020)

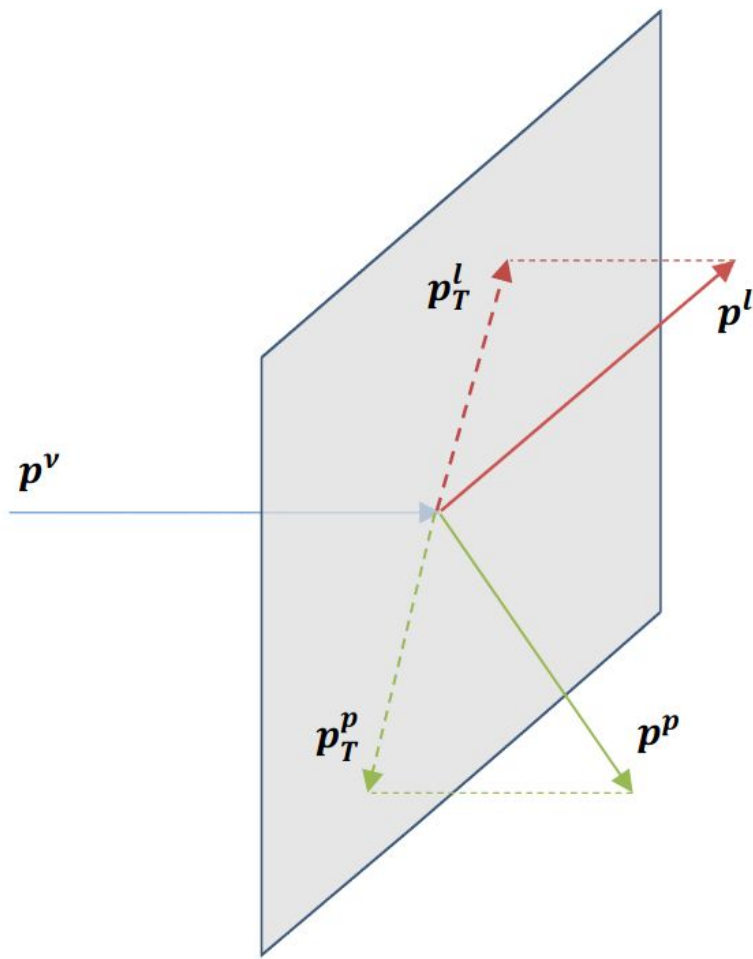


Current Analysis With Much Higher Statistics & Improved Modeling



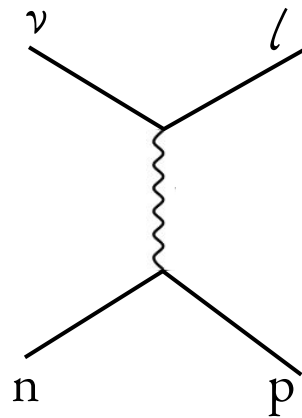
- Largest $\nu_{\mu}^{-40}\text{Ar}$ dataset to date
- Latest version of GENIE Event Generator
[arXiv:2106.09381](https://arxiv.org/abs/2106.09381),
[MICROBOONE-NOTE-1074-PUB](https://arxiv.org/abs/2106.09381)
- Currently finalizing central values & uncertainties
- Also longitudinal variables
- Today, discussion on MC sensitivities

Transverse Components Cancel Out In Absence Of Nuclear Effects

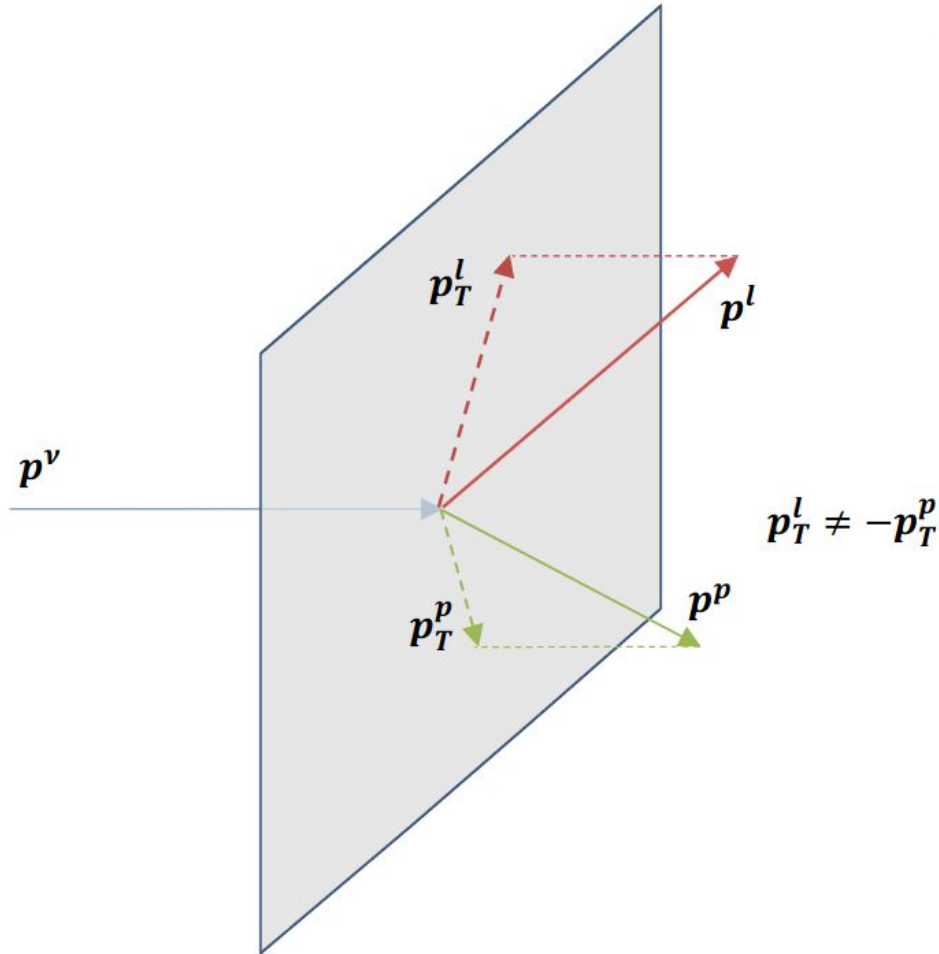


$$p_T^l = -p_T^p$$

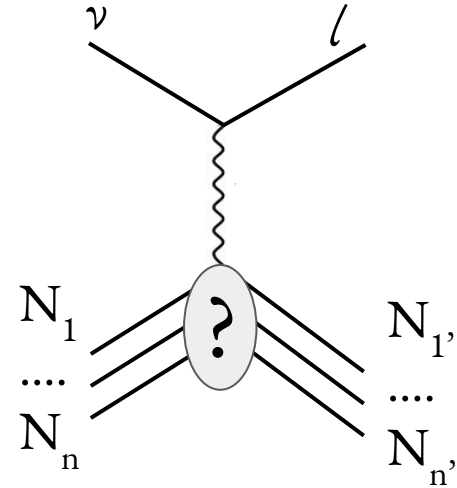
- $\delta p_T = |\mathbf{p}_T^l + \mathbf{p}_T^p| = 0$



Imbalance In The Presence Of Nuclear Effects

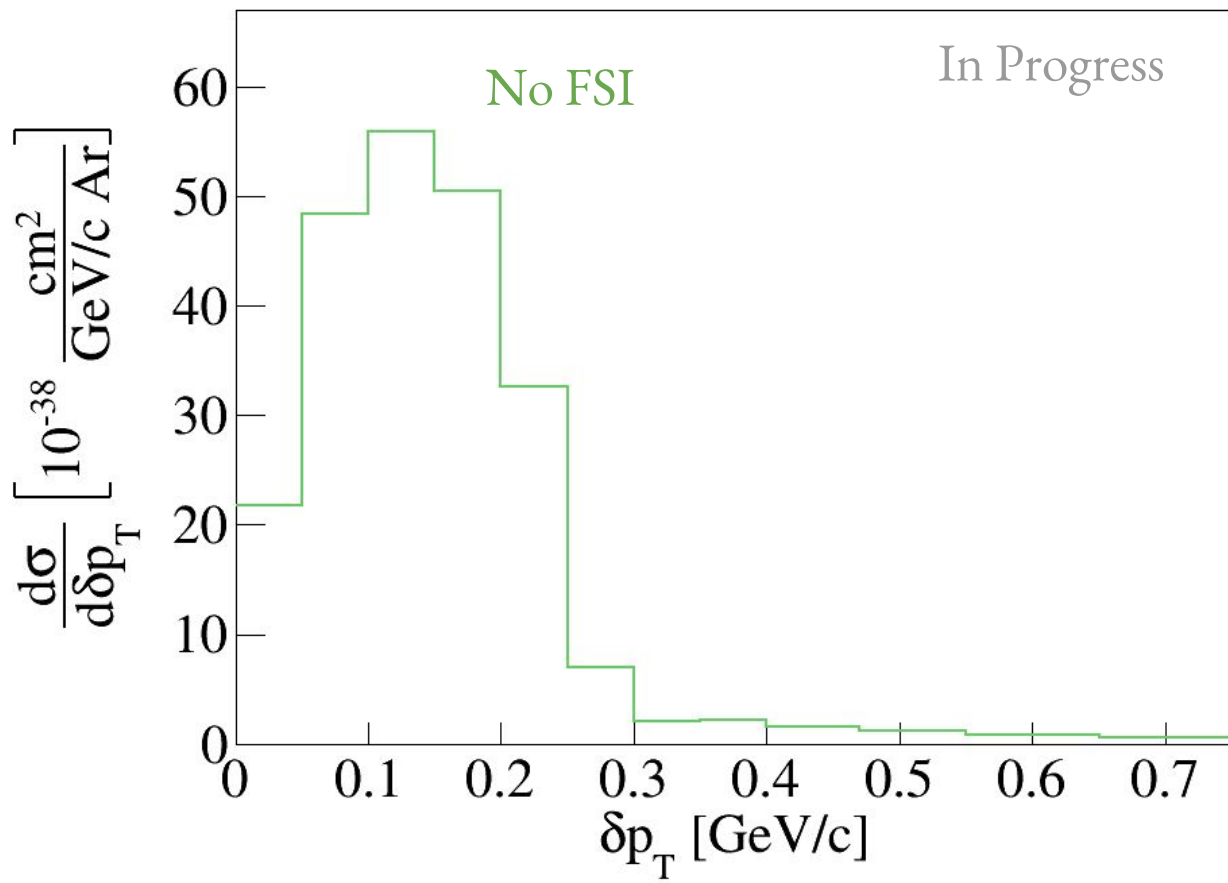


- $\delta p_T = | \mathbf{p}_T^l + \mathbf{p}_T^p | > 0$
proxy for Fermi motion

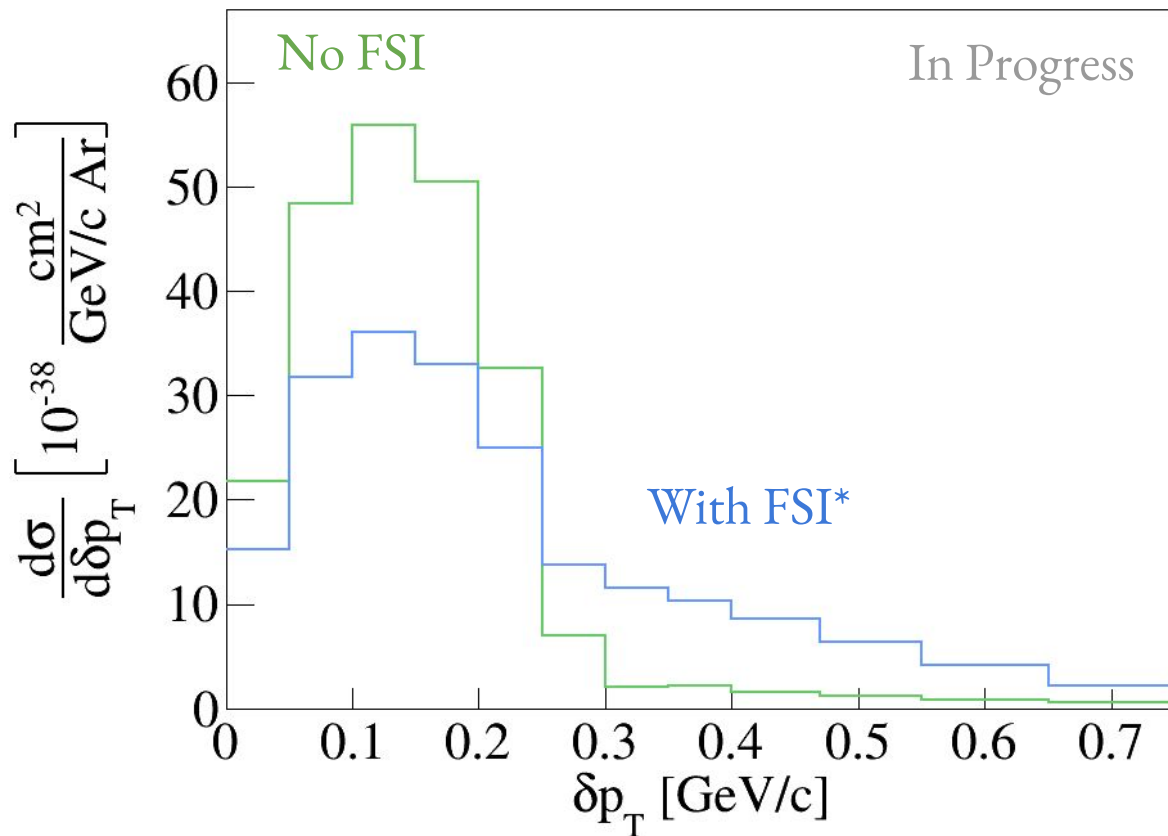


δp_T Probes Fermi Motion

MC uses Local Fermi Gas for ground state

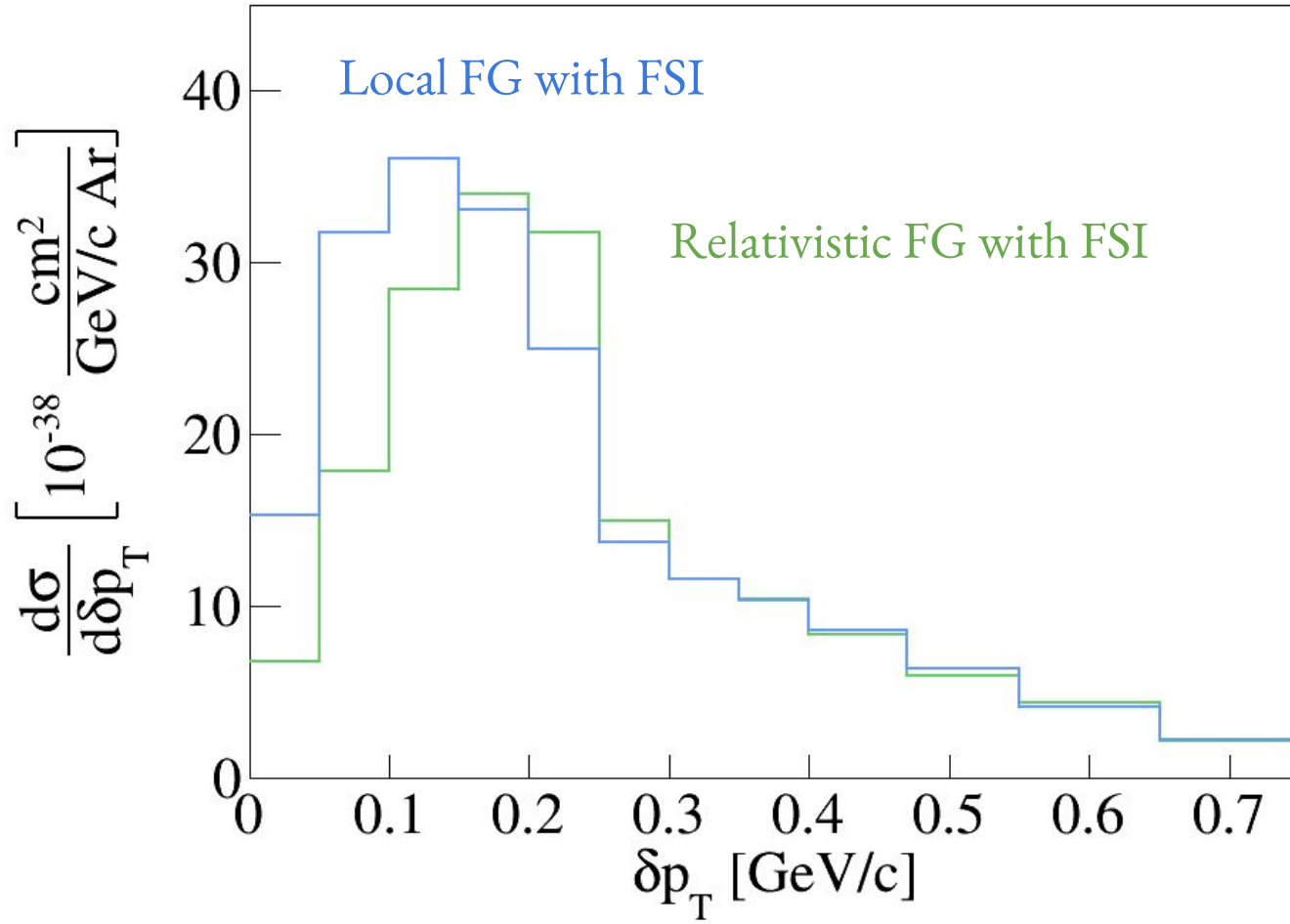


Adding FSI Gives Rise To High Momentum Tail

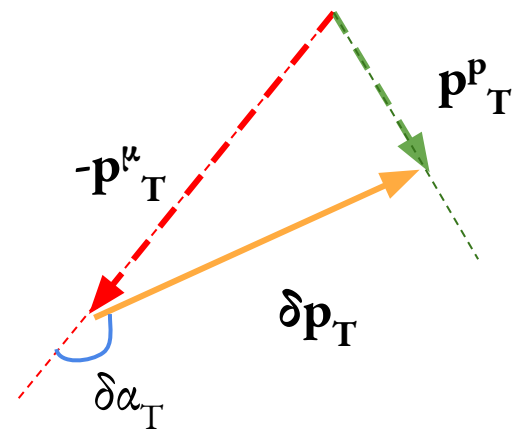
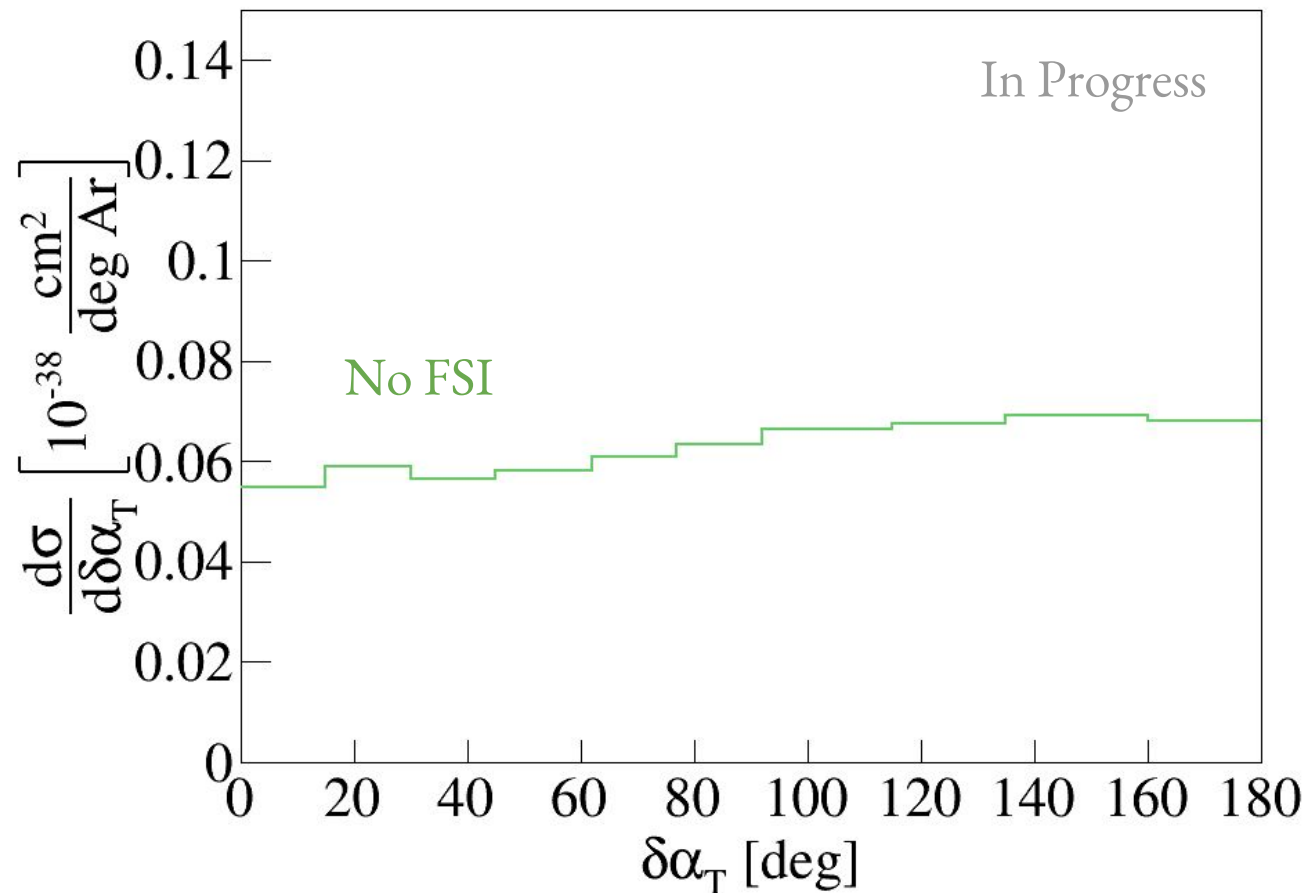


* Used as the nominal MC by the MicroBooNE Collaboration [arXiv:2106.09381](https://arxiv.org/abs/2106.09381), MICROBOONE-NOTE-1074-PUB

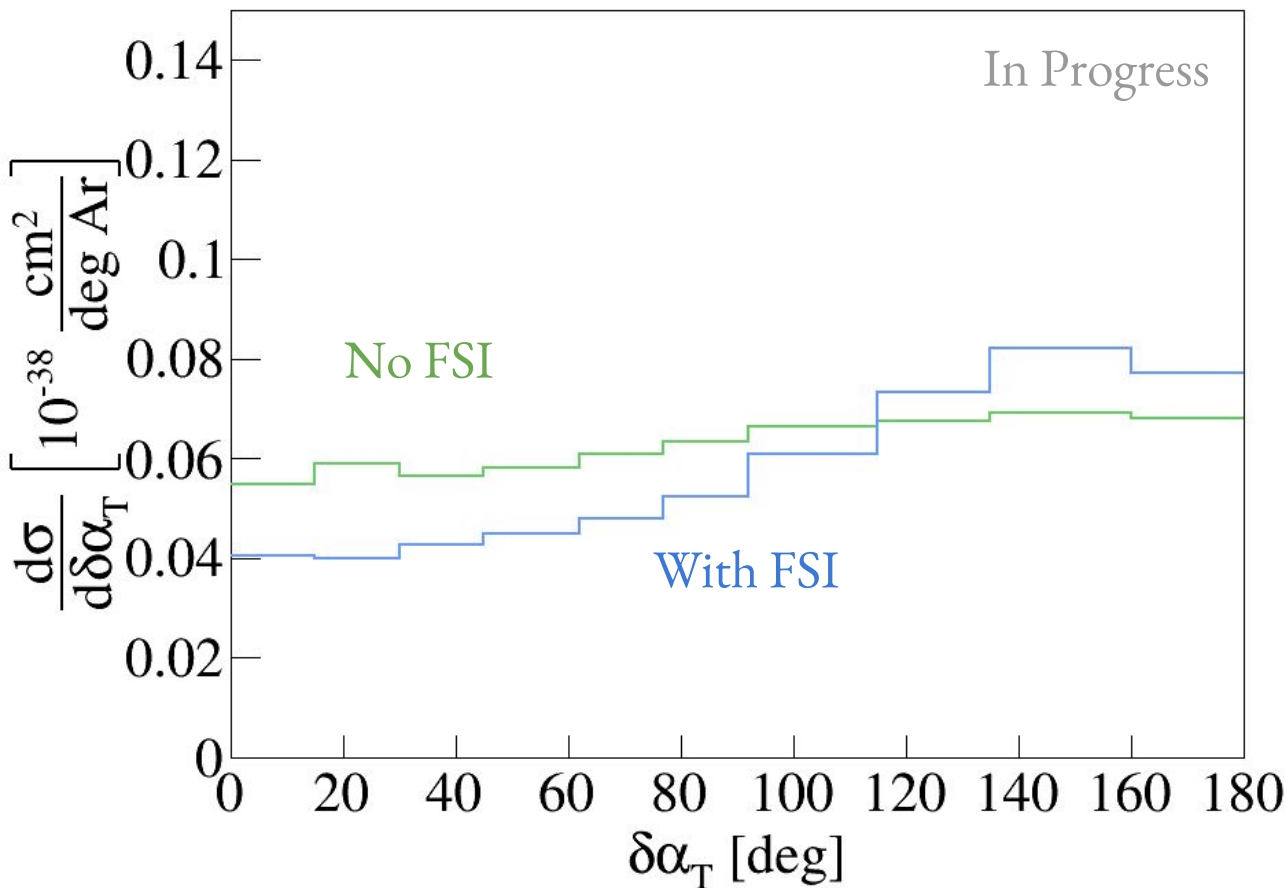
Nuclear Model Shifts Peak Location



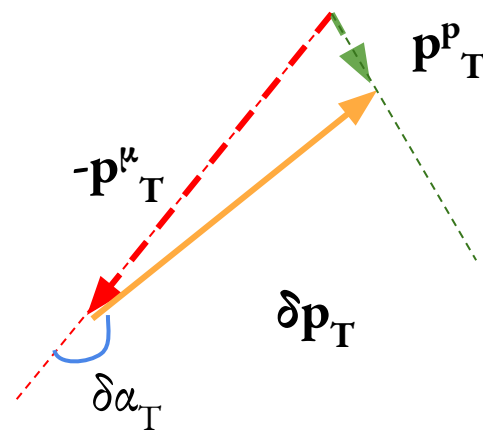
No Preferred $\delta\alpha_T$ Direction Without FSI and $\delta p_T \sim 0$



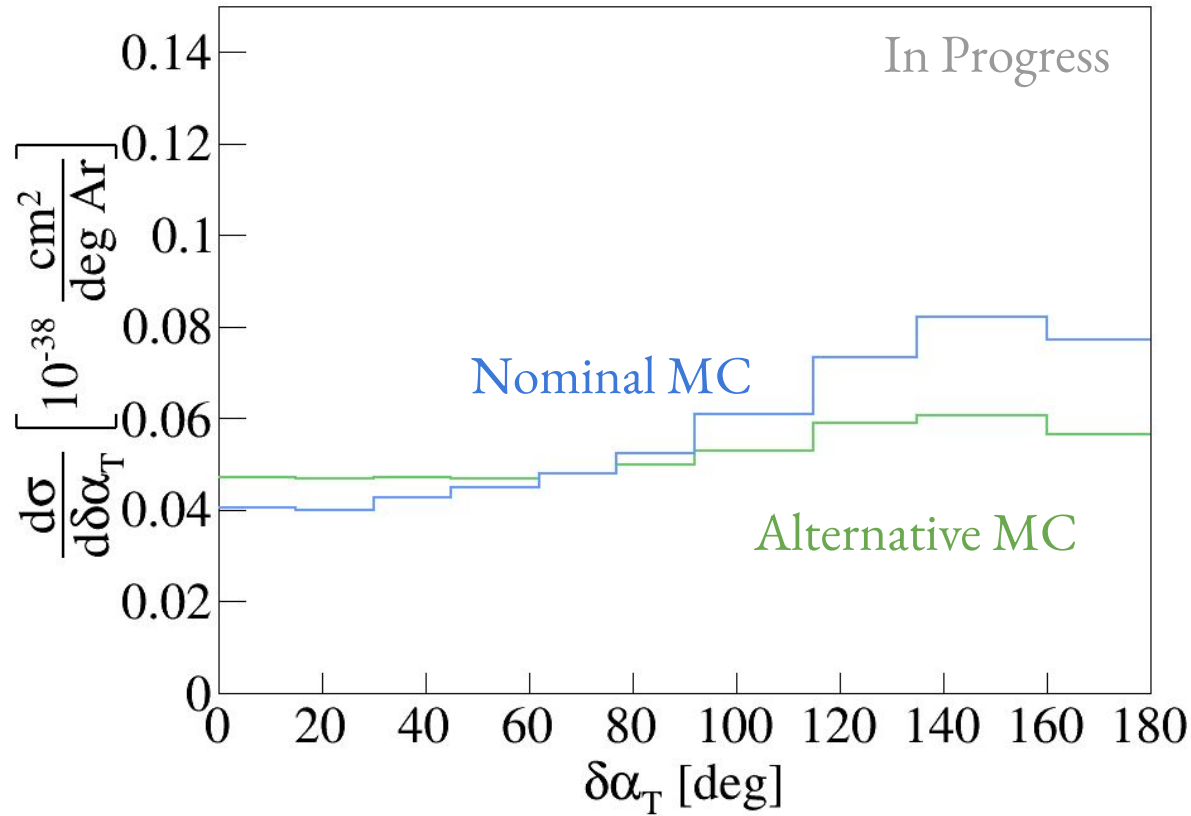
Adding FSI Causes $\delta\alpha_T$ To Rise



Proton “deceleration”
due to FSI



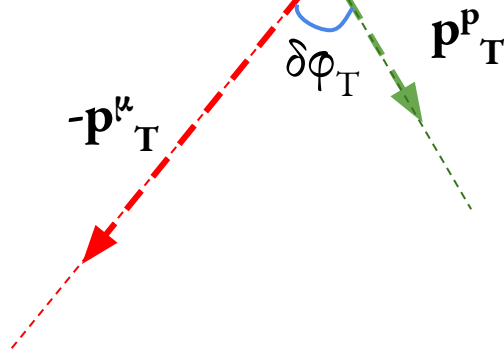
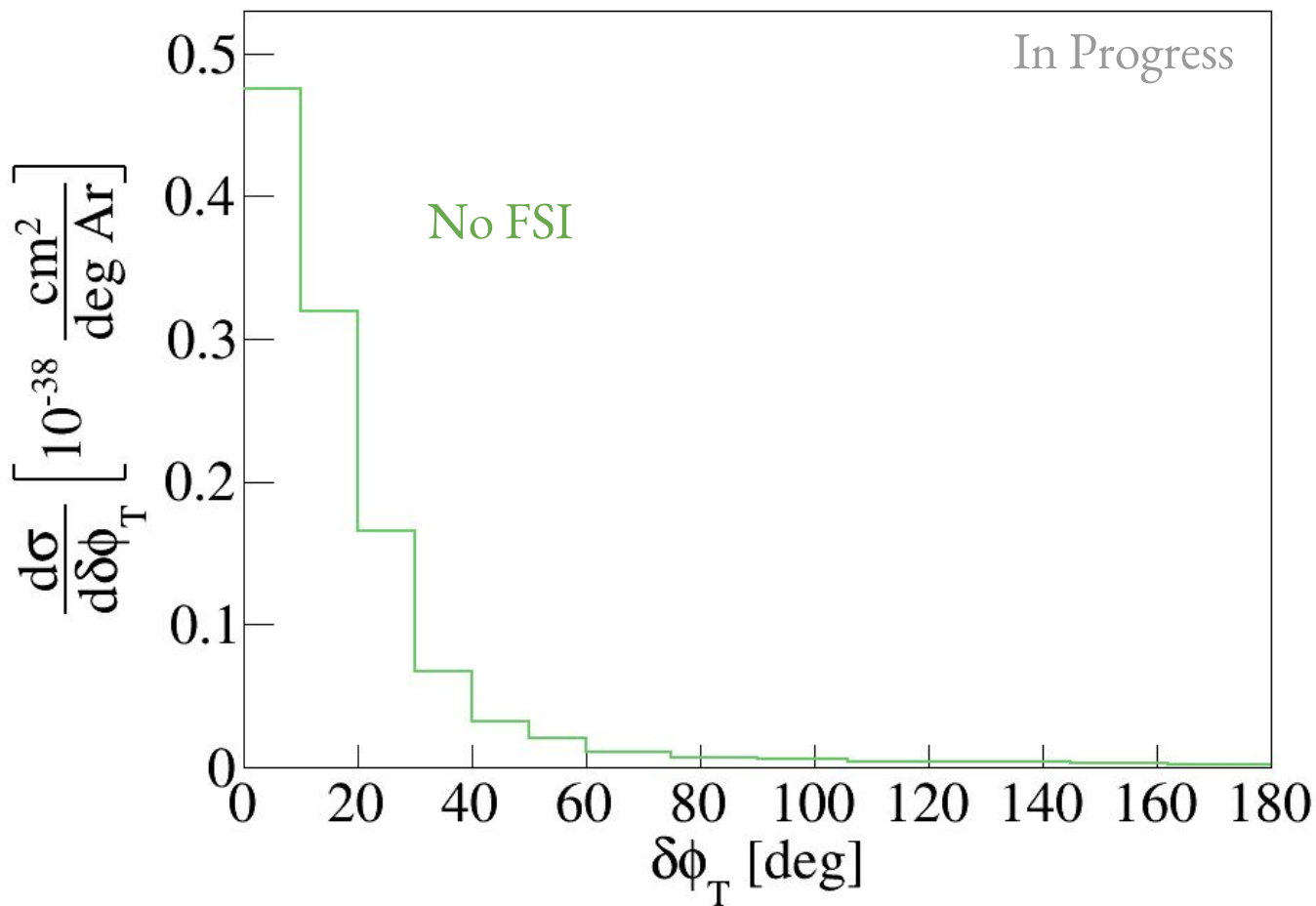
Alternative MC Doesn't Show “FSI Deceleration”



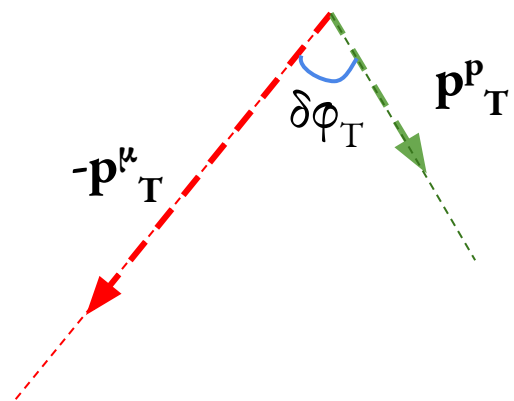
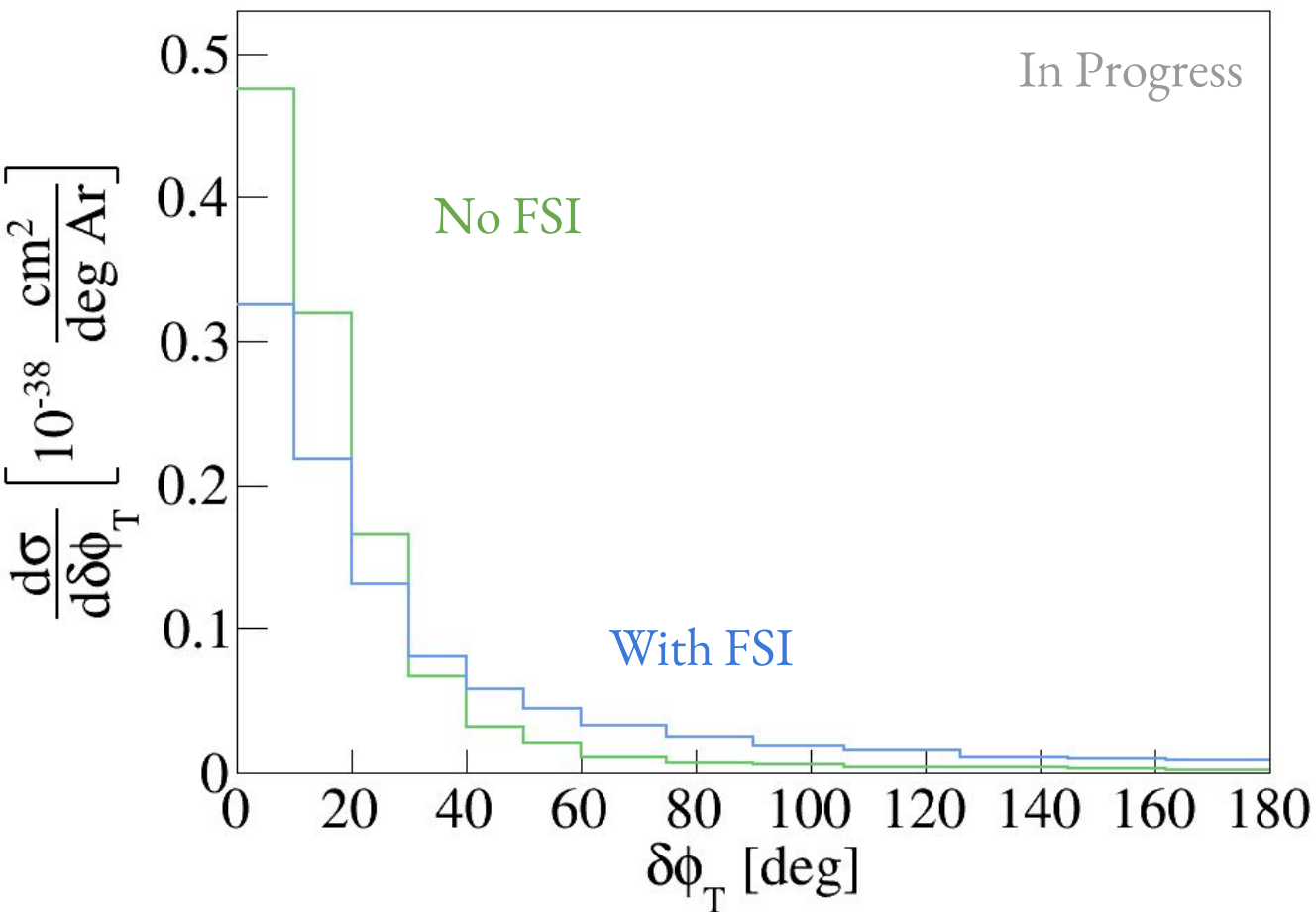
Nominal MC = GENIE v3.0.6 with MicroBooNE Tune [arXiv:2106.09381](https://arxiv.org/abs/2106.09381)

Alternative MC = NuWro [Nucl.Phys.Proc.Suppl. 229-232 \(2012\) 499](https://ui.adsabs.org/abs/2012NuPhS.229-232W)

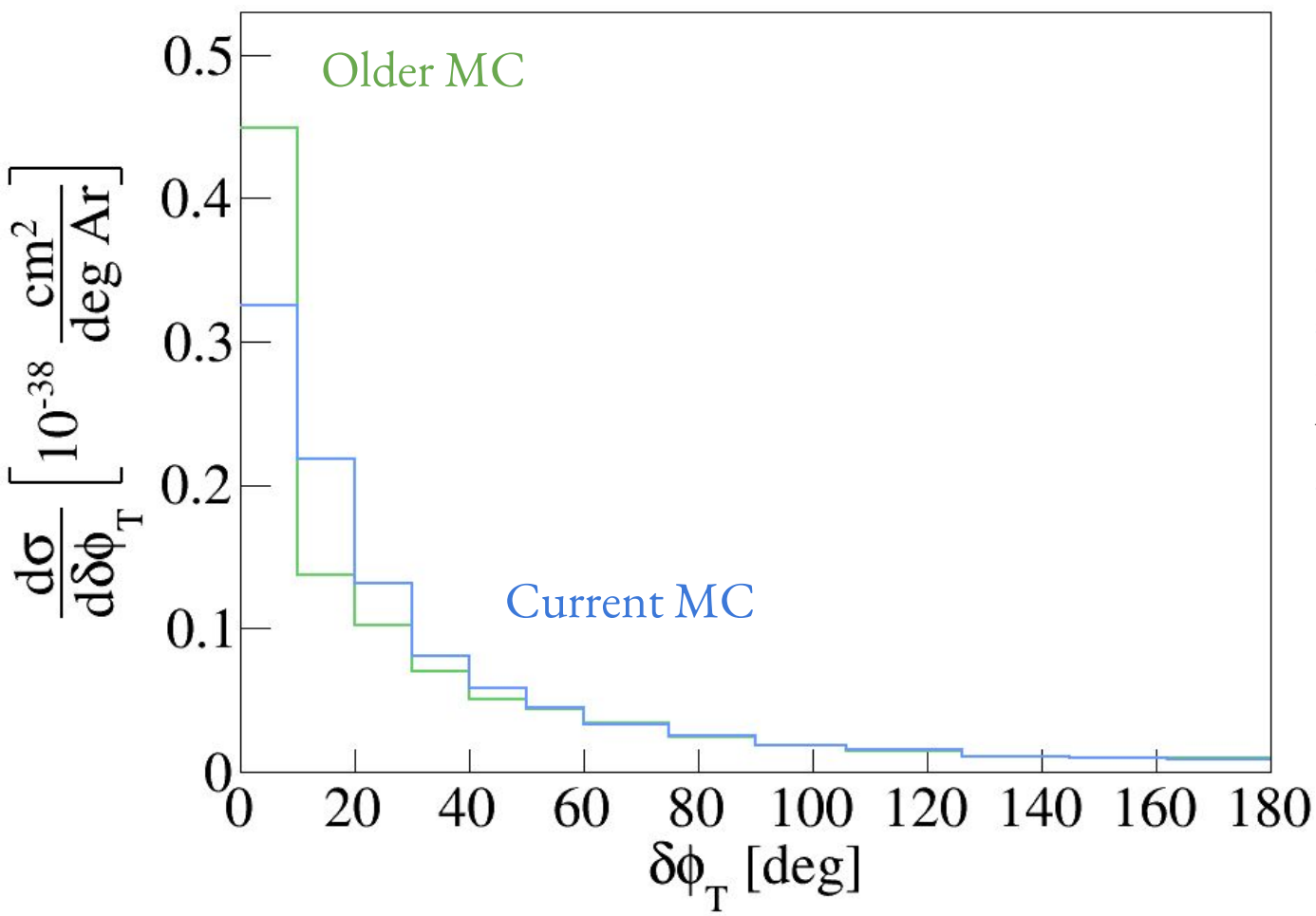
$\delta\phi_T$ Is Small In The Absence Of FSI



Adding FSI Gives Rise To High Angles Tail



MC Versions Show Differences At Small Angles



Older MC = GENIE v2.12.10

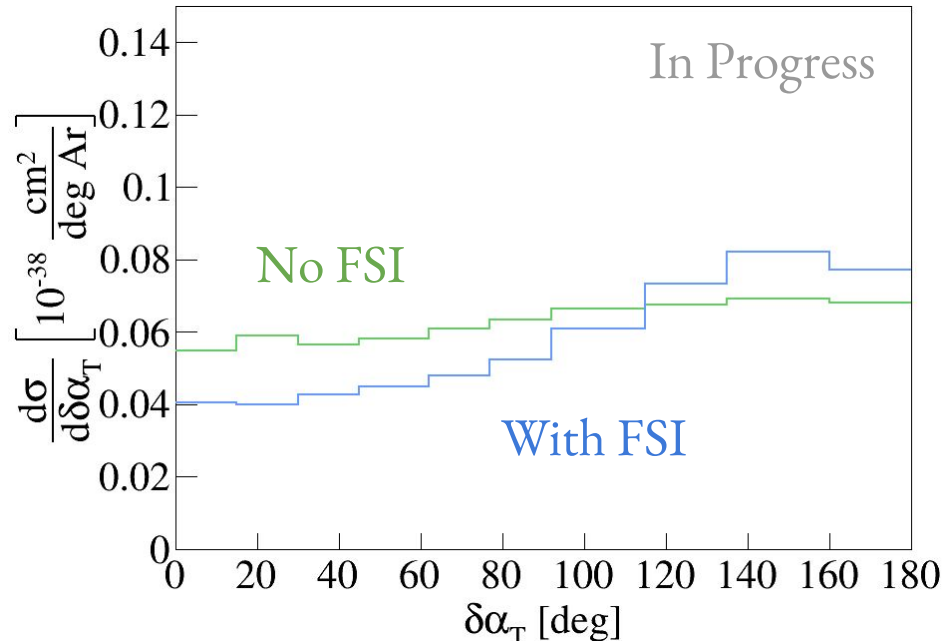
[arXiv:1510.05494](https://arxiv.org/abs/1510.05494)

Current MC = GENIE v3.0.6
with MicroBooNE tune

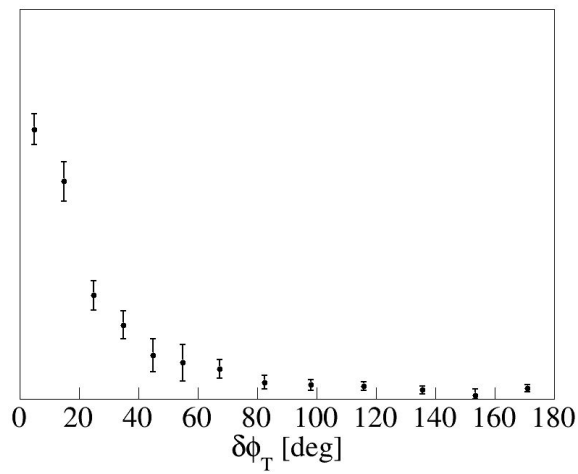
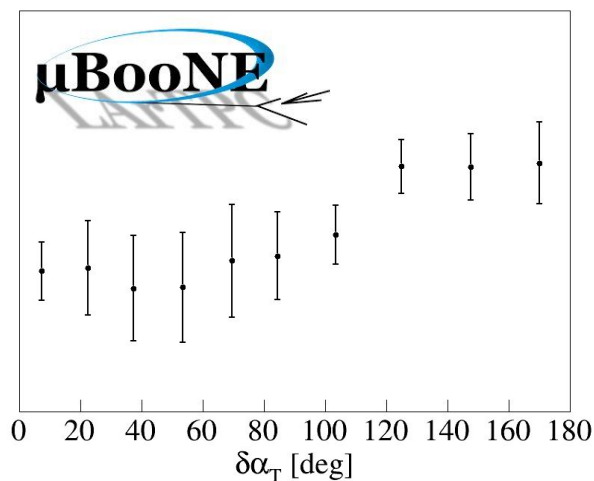
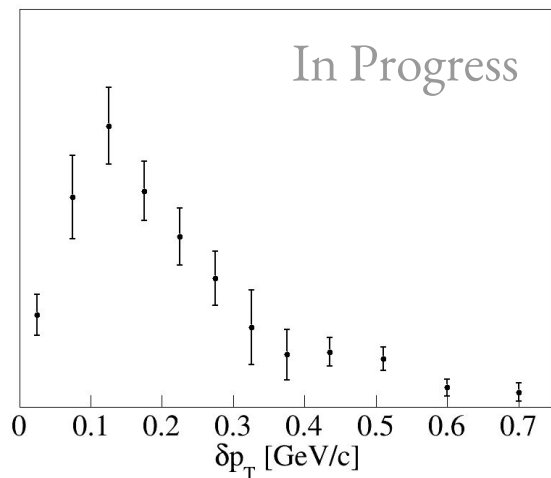
[arXiv:2106.09381](https://arxiv.org/abs/2106.09381)

Wrap Up

- Single transverse variable sensitivity to nuclear models, FSI and multi-nucleon effects
- Powerful tools to reduce cross section uncertainties
- Performed the first CC1p0 π analysis studying these variables on MicroBooNE

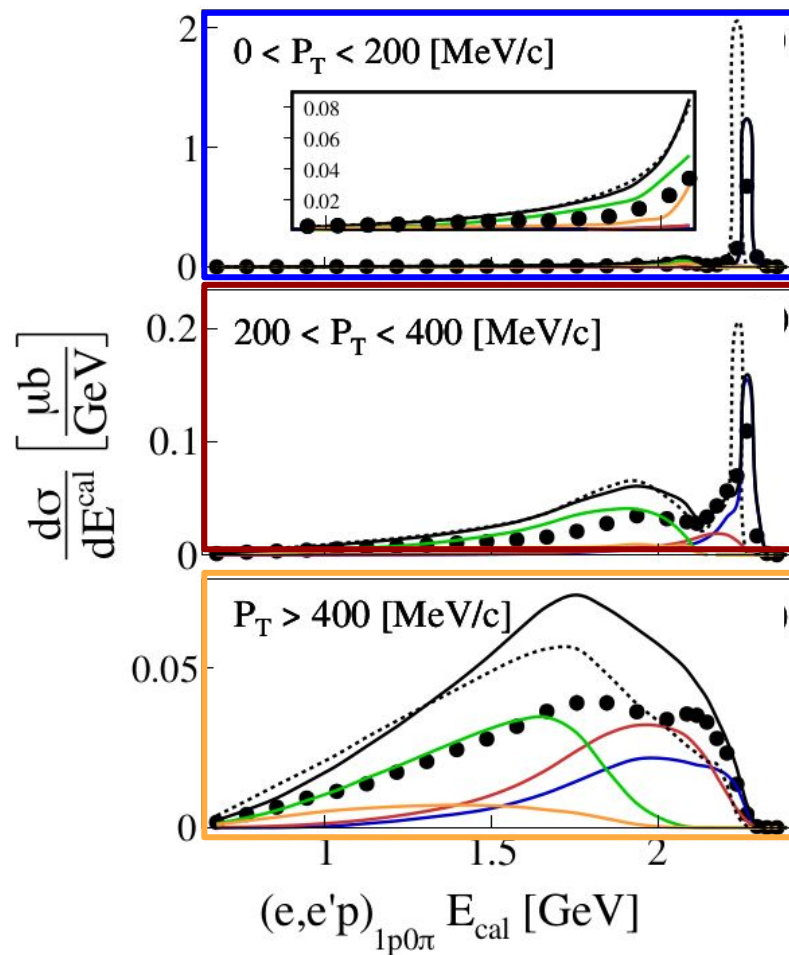
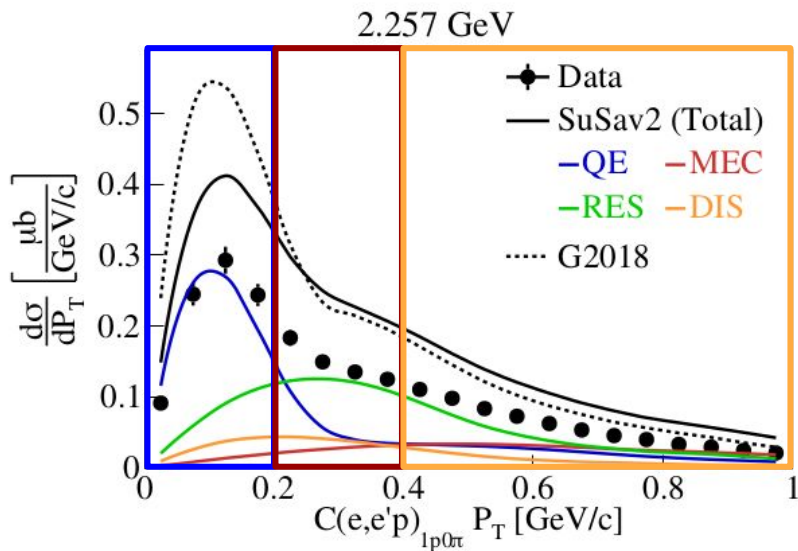


Current Analysis With Much Higher Statistics & Improved Modeling



- Largest ν_μ - ^{40}Ar dataset to date
- Latest version of GENIE Event Generator
[arXiv:2106.09381](https://arxiv.org/abs/2106.09381),
[MICROBOONE-NOTE-1074-PUB](https://microboone.fnal.gov/notes/MICROBOONE-NOTE-1074-PUB)
- Currently finalizing central values & uncertainties
- Today, discussion on MC sensitivities

Connections To Electron Scattering



Khachatryan and Papadopolou et al.
Nature, in process (2021)

μ BooNE

BNB DATA : RUN 5211 EVENT 1225. FEBRUARY 29, 2016

Thank you!

10 cm

Backup Slides

Largest ν_{μ} -Ar Dataset!

Combined Runs	Number of Events	Beam-On Equivalent
BeamOn	10952.00 ± 104.65	10952.00 ± 104.65
MC	36592.00 ± 191.29	6971.48 ± 83.50
CC1p0 π MC	26953.00 ± 164.17	5135.07 ± 71.66
ExtBNB	2396.00 ± 48.95	681.35 ± 26.10
Dirt	184.00 ± 13.56	143.23 ± 11.97



Run 1	Purity (%)	Overall Efficiency (%)	Contained Part Efficiency (%)
CC1p0 π	69.10 ± 0.48	10.70 ± 0.06	28.62 ± 0.17

Single Transverse Variables

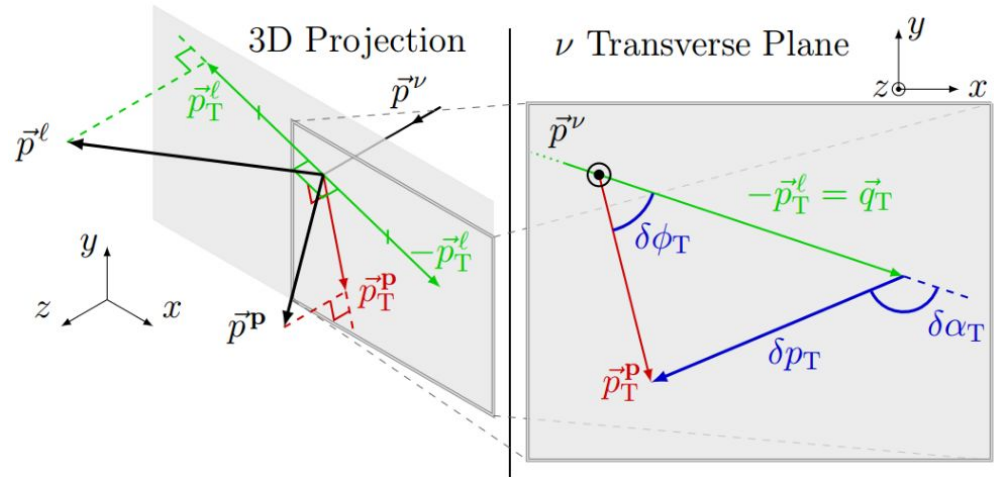
Transverse direction characterized by **magnitude** & **2 angles**

Transverse missing momentum

$$\delta \vec{p}_T = \vec{p}_T^\ell + \vec{p}_T^p$$

$$\delta \phi_T = \arccos \frac{-\vec{p}_T^\ell \cdot \vec{p}_T^N}{p_T^\ell p_T^N}$$

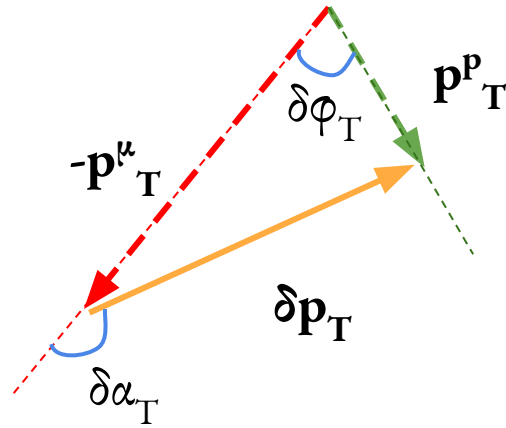
$$\delta \alpha_T = \arccos \frac{-\vec{p}_T^\ell \cdot \delta \vec{p}_T}{p_T^\ell \delta p_T}$$



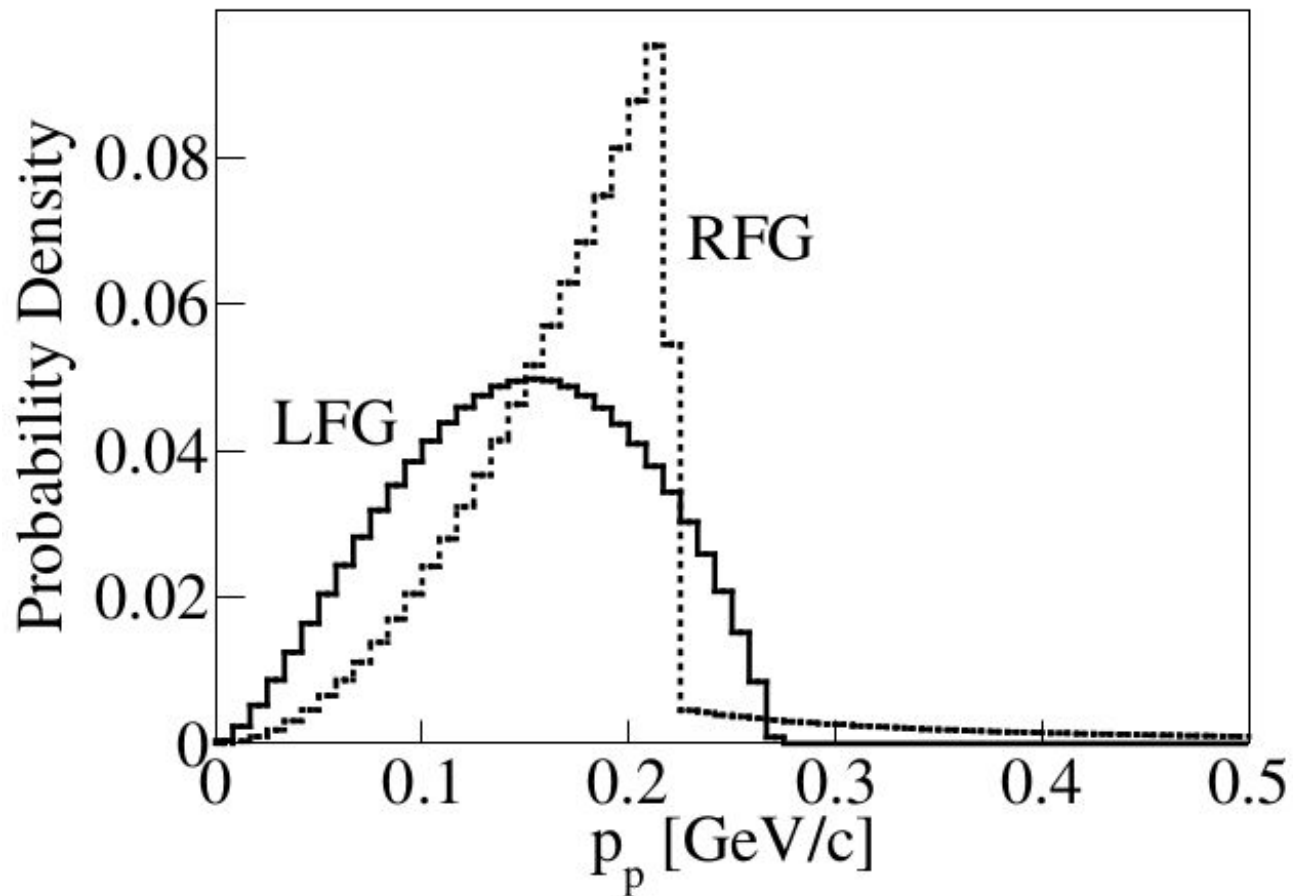
Phys. Rev. C 94, 015503 (2016)

Phys. Rev. Lett. 121, 022504

Single Transverse Variables



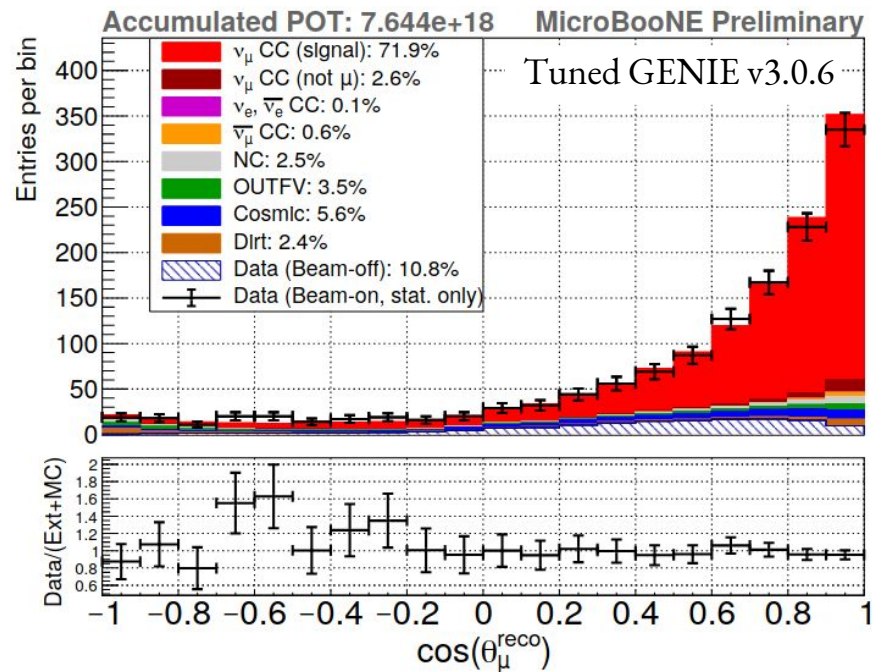
Nuclear Models In The GENIE Event Generator



Better Data/Simulation Agreement From Improved Modeling

- GENIE v2.12.2 \rightarrow GENIE v3.0.6
- Tuned CCQE and CCMEC models to T2K ν_μ CC0 π data
- T2K data is on a carbon target \rightarrow Tuning seems to give good agreement with MicroBooNE's argon-target data

MICROBOONE-NOTE-1074-PUB



Current measurement

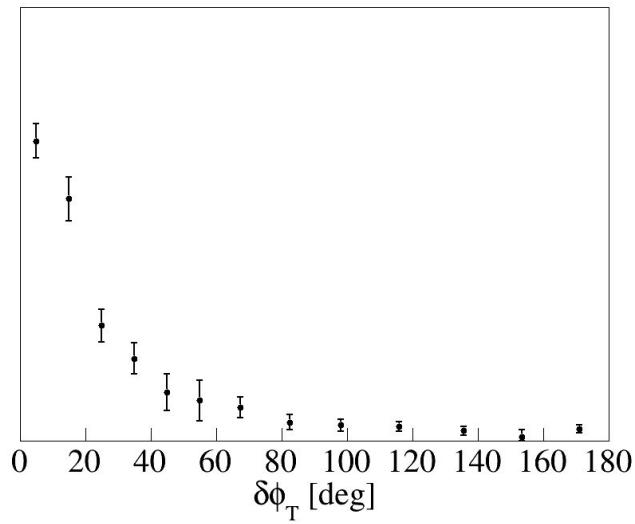
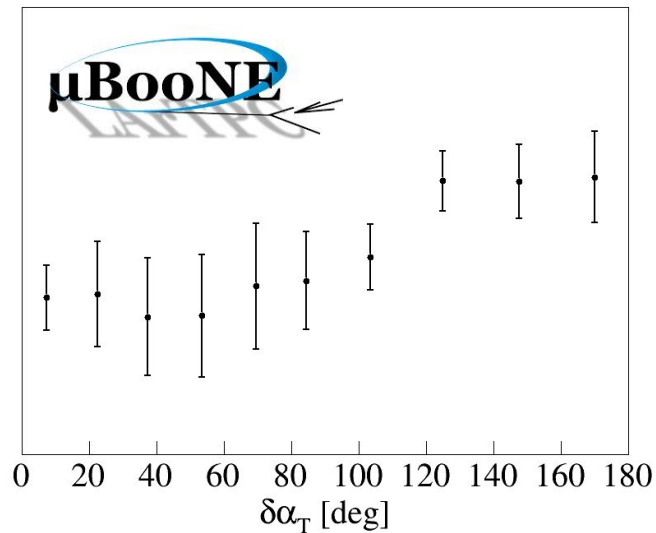
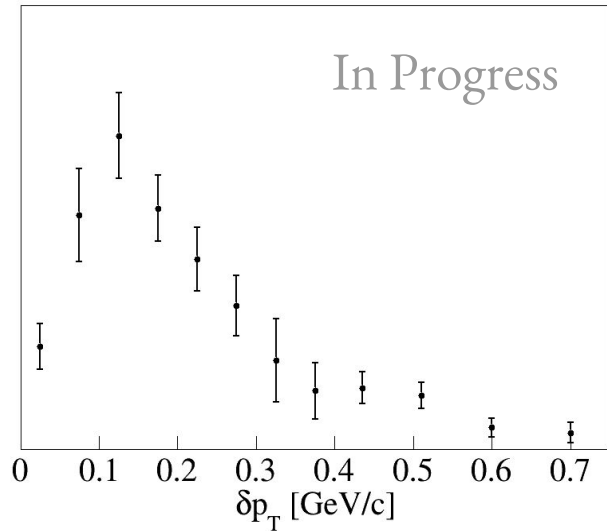
MICROBOONE-NOTE-1069-PUB

GENIE v3.0.6 models used:

QE/MEC → **J. Nieves, J.E. Amaro, M. Valverde** Phys. Rev. C 70, 055503 (2004) and
R. Gran, J. Nieves, F. Sanchez. M. Vicente-Vacas Phys. Rev. D 88, 113007 (2013)

RES/COH → **C. Berger, L. Sehgal** Phys. Rev. D 76, 113004 (2007), Phys. Rev. D 79, 053003 (2009)

FSI → work by **L. Salcedo, E. Oset, M. Vicente-Vacas, C. Garcia-Recio**
Nucl. Phys. A 484, 557-592 (1988) and **V. Pandharipande, S.C. Pieper** Phys. Rev. C 45, 791-798 (1992)



- High statistics & fine binning
- Currently finalizing central values & uncertainties
- Excellent handle to study known unknowns
- Today discussion on MC sensitivities